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Development of On-Farm Anaerobic Digestion

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1. Introduction

Although humankind has always relied on generating energy from biomass in some form (e.g. firewood), it has only recently been re-conceptualised as 'bioenergy'. This is possibly because it was seen as an anachronism in the developed world for most of the last century (Plieninger et al., 2006). About 80% of the world's energy supply is currently derived from fossil fuels, but of the renewable energy sources, biomass is still by far the most important with between 10 to 15% of demand (or about 40-50 EJ per year).

'Biomass' is biological material derived from living, or recently living organisms such as forest residues (e.g. dead trees, branches and tree stumps), green wastes and wood chips. A broader definition of biomass also includes biodegradable wastes and residues from industrial, municipal and agricultural production. It excludes organic material which has been transformed by geological processes into substances such as coal or petroleum. In industrialised countries biomass contributes some 3–13% of total energy supply, but in developing countries this proportion is much higher (up to 50% or higher in some cases).

The recent scientific interest in bioenergy can be traced through three main stages (Leible & Kälber, 2005, cited in Plieninger et al., 2006): the first stage of discussion started with the 1973 oil crisis and the publication of the Club of Rome's report on 'The Limits to Growth'. Along with Rachel Carlson's 'Silent Spring', the Limits to Growth report was an iconic marker of the environmental movement's emergence and a precursor to the concept of sustainable development. The second stage of interest in bioenergy began in the 1980s in Europe as a result of agricultural overproduction and the need to diversify farm income. Triggered by increasing concern over climate change, a third stage started at the end of the 1980s, and continues to this day.

In the early years of expansion in renewable energy technologies, bioenergy was considered technologically underdeveloped compared with wind energy and photovoltaics. Now biomass has proved to be equivalent and in some aspects even superior to other renewable energy carriers. Technological progress facilitates the use of almost all kinds of biomass today – far more than the original firewood use (Plieninger et al., 2006). Biomass has the largest unexploited energy potential among all renewable energy carriers and can be used for the complete spectrum of energy demand – from heat to process energy and liquid fuel, to electricity.

Direct combustion is responsible for over 90% of current secondary energy production from biomass. Biomass combustion is one of the fastest ways to replace large amounts of fossil fuel based electricity with renewable energy sources. Biomass fuels like wood pellets and palm oil can be co-fired with coal or fuel oil in existing power plants. In a number of European countries, heat generated by biomass provides up to 50% of the required heat energy. Wood pellets, have become one of the most important fuels for both private and commercial use. In 2008, approximately 8.6 m tonnes of wood pellets were consumed in Europe (excluding Russia) with a worldwide total of 11.8 m tonnes (German Federal Ministry of Agriculture and Technology, 2009). In Germany, the number of wood pellet heating systems installed in private homes has increased from around 80,000 in 2007 to approximately 105,000 in 2008.

Anaerobic digestion (AD) currently plays a small, but steadily growing role in the renewable energy mix in many countries. AD is the process by which organic materials are biologically treated in the absence of oxygen by naturally occurring bacteria to produce 'biogas' which is a mixture of methane (CH_4) (40-70%) and carbon dioxide (CO_2) (30-60%) plus traces of other gases such as hydrogen, hydrogen sulphide and ammonia. The process also produces potentially useful by-products in the form of a liquid or solid 'digestate'.

It is widely used around the world for sewage sludge treatment and stabilisation where energy recovery has often been considered as a by-product rather than as a principal objective of the process. However, in several European countries anaerobic digestion has become a well established energy resource and an important new farm enterprise, especially now that energy crops are increasingly being used.

2. Historical development of anaerobic digestion

Anecdotal evidence indicates that biogas was used for heating bath water in Assyria during the 10^{th} century BC and in Persia during the 16^{th} century BC (Wellinger, 2007). The formation of gas during the decomposition of organic material was first described by Robert Boyle and Denis Papin in 1682 (Braun, 2007) but it was 1804 by the time John Dalton described the chemical formula for methane.

The first anaerobic digestion plant was built at a leper colony in India in 1859 (Meynell, 1976). By 1895, biogas from sewage treatment works was used to fuel streetlamps in Exeter, England (McCabe & Eckenfelder, 1957). By the 1930's, developments in the field of microbiology led to the identification of anaerobic bacteria and the conditions that promote methane production. Now, tens of thousands of AD plants are in operation at water treatment plants worldwide.

Landfill gas extraction started in the USA in the early 1970s and spread in Europe, mainly in the United Kingdom and Germany (Braun, 2007). There are currently several thousand landfill gas extraction plants in operation worldwide, representing the biggest source of biogas in many countries.

Anaerobic digestion received renewed attention for agri-industrial applications after the 1970s energy crisis (Ni & Nyns, 1996). When AD was first introduced in the 1970s and 80s, failure rates were very high (Raven & Gregersen, 2007). AD-plant failures were mainly attributed to poor design, inadequate operator training and unfavourable economics (either as a result of unfavourable economies of scale or an unreliable market for biogas). In many parts of the world, these initial experiences have now been overcome with better and more robust reactor designs and with more favourable economic incentives for biogas utilisation.

In developing countries, AD is closely connected with sustainable development initiatives, resource conservation efforts, and regional development strategies (Bi & Haight, 2007; Wang

& Li, 2005). Rural communities in developing countries generally employ small-scale units for the treatment of night soil and to provide gas for cooking and lighting for a single household. Nepal is reported to have some 50,000 digesters and China is estimated to have 14 million small-scale digesters (Wellinger, 2007). Bi & Haight (2007) described a typical household digester in Hainan province (China) to be of concrete construction, about 6m^3 in size and occupying an area of about 14m^2 in the backyard. Digesters are connected with household toilets and the livestock enclosure so that both human and animal manure can flow directly into the digesters. Agricultural straw is also often utilised as feedstock. The digesters are connected to a stove in the house by a plastic pipeline.

Before the introduction of AD, the majority of villagers had relied heavily on the continuous use of firewood, agricultural residues and animal manure in open hearths or simple stoves that were inefficient and polluting. The smoke thus emitted contains damaging pollutants, which may lead to severe illness, including pneumonia, cancer, and lung and heart diseases (Smith, 1993). Combustion of biomass in this way is widespread throughout the developing world and it is estimated to cause more than 1.6 million deaths globally each year (400,000 in Sub-Saharan Africa alone), mostly among women and children (Kamen, 2006). In contrast, biogas is clean and efficient with carbon dioxide, water and digestate as the final by-products of the process. It also conserves forest resources since demand for firewood is lessened when AD is introduced.

2.1 Two models of on-farm anaerobic digestion

Agricultural AD plants are most developed in Germany, Denmark, Austria and Sweden. There are two basic models for the implementation of agriculture-based AD plants in the EU (Holm-Nielsen et al., 2009):

- Centralised plants that co-digest animal manure collected from several farms together with organic residues from industry and townships. These plants are usually large scale, with digester capacities ranging from a few hundred to several thousand cubic meters.
- Farm-scale AD plants co-digesting animal manure and, increasingly, bioenergy crops from one single farm or, sometimes two or three smaller neighbouring farms. Farm-scale plants are usually established at large pig farms or dairy farms.

Centralised AD plants are a unique feature of the Danish bioenergy sector. According to Holm-Nielsen et al. (2009), the Danish AD production cycle represents an integrated system of renewable energy production, resource utilisation, organic waste treatment and nutrient recycling and redistribution. In 2009, there were 21 centralised AD plants and 60 farm-scale plants in Denmark (Holm-Nielsen, 2009). With recent increases in financial incentives provided by the Danish Government, biogas production is expected to triple by 2025 and the number of centralised plants will increase by about 50 (Holm-Nielsen & Al Seadi, 2008; Holm-Nielsen, 2009).

Farm-scale AD plants typically use similar technologies to the centralised plant concept but on a smaller scale. Germany is an undisputed leader in the application of on-farm AD systems with over 4,000 plants currently in operation. The German government also has ambitious plans to expand these numbers even further in order to meet a target of 30% renewable energy production by 2020 (Weiland, 2009). In order to meet this target, the number of AD plants will need to increase to about 10,000 to 12,000. Photovoltaics and wind

energy are also widely distributed on farms throughout Germany. It is not uncommon to see an AD plant, a wind turbine and photovoltaics on a single farm (Fig. 1).
Approximately 80% of the biomass used in these plants is manure (mainly slurry), co-digested with 20% organic waste made up of plant residue and agro-industrial waste (da Costa Gomez & Guest, 2004). The biogas is mainly used for combined heat and power (CHP) generation, with the heat generated being used locally for district heating. Biogas is also sometimes up-graded to natural gas quality for use as a vehicle fuel, a practice that is now increasingly common in Sweden (Lantz et al., 2007; Persson et al., 2006).

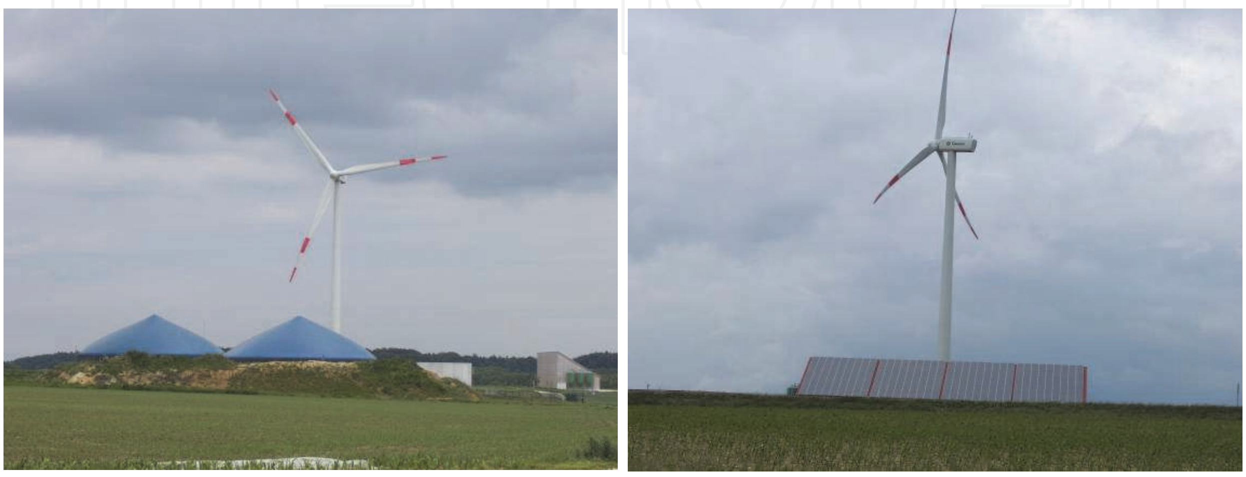

Fig. 1. "Energy farming in Germany". A single farm is shown here combining an AD plant, wind turbines and photovoltaics on farm buildings. Photo: J. Biala

2.2 Drivers for investment in on-farm anaerobic digestion

Local conditions are particularly important to the decisions of farmers with respect to investing in renewable energy technologies (Ehlers, 2008; Khan, 2005; Raven & Gregersen, 2007). The two most important issues regarding biomass use for energy production in most countries are economic growth and the creation of regional employment. Avoiding carbon emissions, environmental protection and security of energy supply are often big issues on the national and international stage, but the primary driving force for local communities are much more likely to be employment or job creation, contribution to regional economy and income improvement (Domac et al., 2005). The flow-on benefits from these effects are increased social cohesion and stability through the introduction of a new employment and income generating activity.
A range of policy instruments has been used by different countries seeking to develop their renewable energy industries, including renewable energy certificate trading schemes, premium feed-in-tariffs, investment grants, soft loans and generous planning provisions (Thornley & Cooper, 2008). In particular, Germany's generous feed-in-tariffs for renewable energy are typically credited with the massive expansion of on-farm AD plants in that country. Germany introduced the feed-in tariff model in 1991, obliging utilities to buy electricity from producers of renewable energy at a premium price. The feed-in tariff law has been continually revised and expanded. The premium price is technology dependent and is guaranteed for 20 years with a 1% digression rate built in to promote greater efficiency. Investors therefore have confidence in the prospective income from any newly

proposed renewable energy project and can develop a more solid business case for obtaining finance.

Whilst the feed-in tariff law has had a marked impact on the diffusion of on-farm AD in Germany, a more complete picture emerges when the underlying political, institutional and socio-economic drivers in the country are considered (Wilkinson, 2011). For example, energy security and climate change mitigation are major geopolitical drivers in Germany. In addition, the impact of the EU's Common Agricultural Policy has been profound in driving both political and grass-roots efforts to develop alternative approaches to farming, including on-farm bioenergy production (Plieninger et al., 2006).

3. Overview of the anaerobic digestion process

The microbiology of the AD process is very complex and involves 4 stages (Fig. 2). The first stage of decomposition in AD is the liquefaction phase or hydrolysis, where long-chain organic compounds (e.g. fats and carbohydrates) are split into simpler organic compounds like amino acids, fatty acids and sugars. The products of hydrolysis are then metabolised in the acidification phase by acidogenic bacteria and broken down into short-chain fatty acids (e.g. acetic, proprionic and butyric acid). Acetate, hydrogen and carbon dioxide are also created and act as initial products for methane formation. During acetogenesis, the organic acids and alcohols are broken down into acetic acid, hydrogen and carbon dioxide. These products act as substrates for methanogenic microorganisms that produce methane in the fourth and final phase called (methanogenesis).

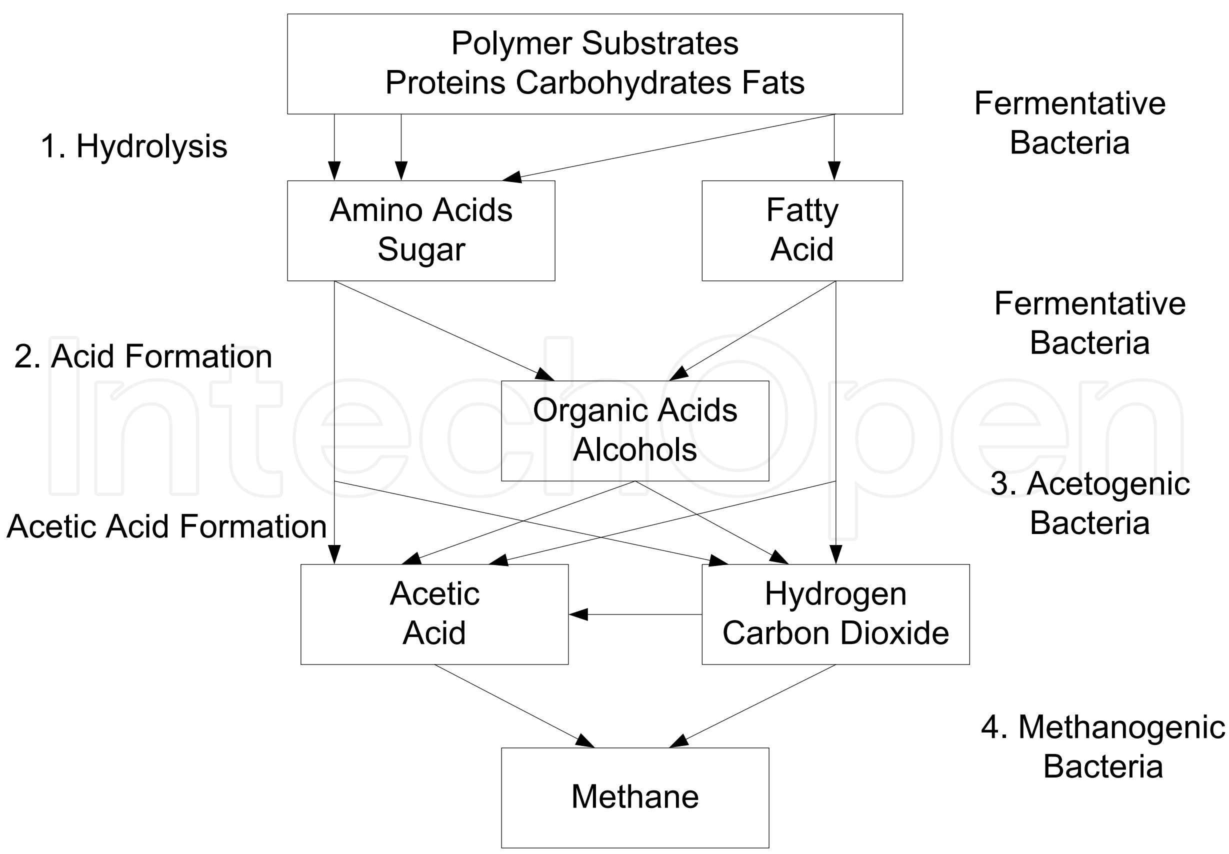

Fig. 2. Stages in anaerobic digestion. Source: Prof. M. Kranert, Univ Stuttgart.

AD systems usually operate either in the mesophilic (35-40ºC) or the thermophilic temperature (50-60ºC) ranges. Operating in the thermophilic temperature range reduces hydraulic retention time (HRT or treatment time) to as low as 3-5 days[1] and more effectively contributes to the sanitisation of the organic waste streams (i.e. improves pathogen and weed-seed destruction). However, greater insulation is necessary to maintain the optimum temperature range, and more energy is consumed in heating thermophilic systems. Larger, centralised systems typically run at thermophylic temperatures. Mesophylic systems need a longer treatment time to achieve good biogas yields but these systems can be more robust than thermophilic systems.

4. Anaerobic digestion systems

AD systems are relatively simple from the process engineering point of view, since fermentation is driven by a "mixed culture" of ubiquitous organisms, and no culture enrichment is generally required (Braun, 2007). Instead, the course of fermentation is controlled by the conditions at start-up: temperature, substrate composition, organic loading rate and hydraulic retention time. Since methane is fairly insoluble in water it separates itself from the aqueous phase and accumulates in the head space of the reactor and is easily collected from there.

A generalised, simplified scheme of the process typical of European systems (Fig. 3) comprises 4 steps:

- substrate delivery, pre-treatment and storage,
- digestion,
- digestate use, and
- energy recovery from biogas.

Usually the effluent leaves the digester by gravity flow and in most cases undergoes further digestion in a second reactor. A tank stores digestate for many months before it is applied directly to farming land. Sometimes the digestate is dewatered prior to undergoing further treatment and disposal (e.g. composting) and the liquid fraction is used as a fertiliser. The head space of the digestate storage tank is typically also connected to the gas collection system. Biogas is collected in both digestion reactors and stored in gas storage tanks or, more frequently in the head space of the second digester, covered with a floating, gas tight membrane. Depending on its final use, biogas can undergo several purification steps. Desulphurisation (to remove corrosive H_2S) is required before the biogas can be combusted in burners or used in combined heat and power (CHP) plants. Desulphurisation can be simply achieved by the controlled addition of air into the digester head space. If biogas is intended for use as a transport fuel or to be fed into the natural gas grid, further upgrading to remove CO_2 is required (Fig. 3).

4.1 System designs

In a batch system, biomass is added to the digester at the start and is sealed for the duration of the process. High-solids systems (total solids content up to 40%) are examples of batch systems. These systems are becoming more widespread for the treatment of municipal

[1] E.g. High-rate anaerobic digestion of waste water. Longer HRTs are typical for semi-solid and solid organic waste streams.

wastes in some parts of Europe (Braun, 2007). In these systems, the solid feedstock is loaded into several reactor cells in sequence. These systems are relatively cheap to construct, require little additional water to operate but the remaining digestate often requires intensive treatment by aerobic composting.

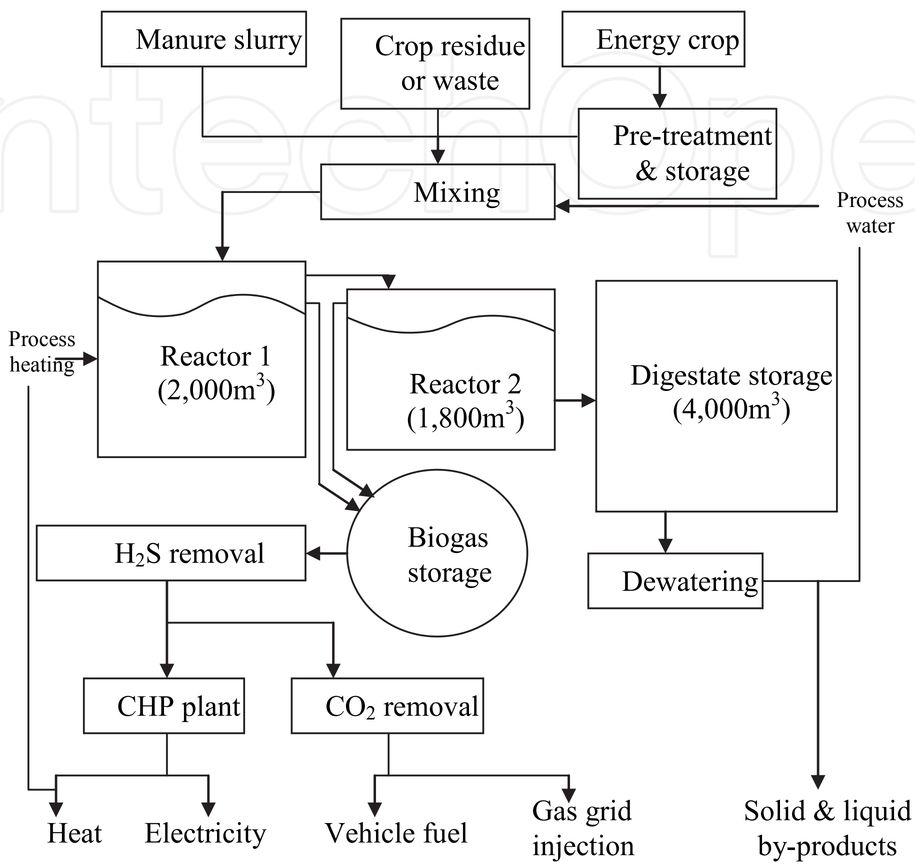

Fig. 3. Typical process-flow diagram for the European 2-stage anaerobic digestion process. CHP – combined heat and power. Source: Wilkinson (2011).

In continuous digestion processes, organic matter is added constantly or in stages to the reactor. Here the end products are constantly or periodically removed, resulting in constant production of biogas. Examples of this form of anaerobic digestion include, covered lagoons, plug-flow digesters, continuous stirred-tank reactors (CSTRs), upflow anaerobic sludge blanket (UASB), expanded granular sludge bed (EGSB) and internal circulation reactors (IC). The most common systems used world-wide for processing manure slurries and agricultural residues are covered lagoons and plug-flow digesters (particularly in North America) and continuous stirred-tank reactors (in Europe and North America). UASB, EGSB and IC reactors are more commonly associated with the anaerobic digestion of wastewater at municipal water treatment plants and will therefore not be discussed in detail here.

Covered lagoon digesters are the cheapest available AD systems. About 19 of the approximately 140 on-farm digesters in the USA are of this type (USEPA, 2009). They can be a viable option at livestock operations in warm climates discharging manure in a flush management system at 0.5-2% solids. The in-ground, earth or lined lagoon is covered with a flexible or floating gas tight cover. Retention time is usually 30-45 days or longer depending on lagoon size. Very large lagoons in hot climates can produce sufficient quantity, quality and consistency of gas to justify the installation of an engine and generator. Otherwise gas production can be less consistent and the low quality gas has to be flared off much of the year.

Plug-flow digesters are also common in the USA where they make up more than half of the on-farm AD plants currently in operation (USEPA, 2009). A plug-flow digester is a long narrow insulated and heated tank made of reinforced concrete, steel or fiberglass with a gas tight cover to capture the biogas. These digesters operate at either mesophilic or thermophilic temperatures. The plug flow digester has no internal agitation and is loaded with thick manure of 11–14% total solids. This type of digester is suited to scrape manure management systems with little bedding and no sand. Retention time is usually 15 to 20 days. Manure in a plug flow digester flows as a plug, advancing towards the outlet whenever new manure is added.

Continuous stirred-tank reactors are most commonly used for on-farm AD systems in Europe (Braun, 2007) and about a quarter of on-farm digesters in the USA are of this type (USEPA, 2009). This type of digester is usually a round insulated tank made from reinforced concrete or steel, and can be installed above or below ground. The contents are maintained at a constant temperature in the mesophilic or thermophilic range by using heating coils or a heat exchanger. Mixing can be accomplished by using a motor driven mixer, a liquid recirculation pump or by using compressed biogas. A gas tight cover (floating or fixed) traps the biogas. The CSTR is best suited to process manure with 3-10% total solids and retention time is usually 10-20 days.

5. Use of digestate

One advantage attributed to farm-based AD systems is the transformation of the manure into digestate, which is reported to have an improved fertilisation effect compared to manure (Börjesson & Berglund, 2003, 2007), potentially reducing the farmer's requirements for commercial fertilisers. The use of digestate instead of commercial fertilisers is also encouraged in Sweden by a tax on the nitrogen in commercial fertilisers (Lantz et al., 2007). However, these incentives are weakened by the limited knowledge and practise of using digestate, as well as the higher handling costs connected with the digestate compared with commercial fertilisers.

In order to control the quality of digested manure, the three main components of the AD cycle must be under effective process control: the feedstock, the digestion process, and the digestate handling/storage (Al Seadi, 2002). The application of digestate as fertiliser must be done according to the fertilisation plan of the farm. Inappropriate handling, storage and application of digestate as fertiliser can cause ammonia emissions, nitrate leaching and overloading of phosphorus. The nitrogen load on farmland is regulated inside the EU by the Nitrates Directive (91/676/EEC nitrate) which aims to protect ground and surface water from nitrate pollution. However, the degree of implementation of the Nitrates Directive in EU member countries varies considerably (Holm-Nielsen et al., 2009).

6. Maximising biogas yields with co-digestion

A key factor in the economic viability of agricultural AD plants is the biogas yield (often expressed as m^3 biogas produced per kg of volatile solids (VS) added). Traditional AD systems based solely on manure slurries can be uneconomic because of poor biogas yields since manure from ruminants is already partly digested in the gut of the animal. Whilst a wide range of substrates can be theoretically digested, biogas yields can vary substantially (Table 1). To put this into perspective, if 1 m^3 of biogas per m^3 of reactor volume is produced per day from digesting manure alone, between 2 to 3 m^3 biogas per m^3 per day can be produced if energy-rich substrates such as crop residues and food wastes are used.

Centralised AD plants receiving agri-industrial and/or municipal wastes as well as farm-based residues also receive an additional gate fee for the wastes they receive. However, where bioenergy crops are grown, economic viability is affected by the cost of growing the crops, any economic incentives provided to grow them and the quality of the final substrate. The cost of supplying energy crops for biogas plants has been increasing in recent years in the EU due to high world food prices rather than competition for land (Weiland, 2008). Data from Germany showed that the cost of supplying maize for silage (minus transport and ensiling) rose 83% between October 2007 and October 2008 (Weiland, 2008).

Although co-digestion with energy crops is not a new concept, it was first considered not to be economically feasible (Braun, 2007). Instead, crops, plants, plant by-products and waste materials were added occasionally just to stabilise anaerobic digesters. However, with steadily increasing oil prices and the improved legal and economic incentives emerging in the 1990s, energy crop R&D was stimulated, particularly in Germany and Austria. Now, 98% of on-farm digesters in Germany utilise energy crops as a substrate (Weiland 2009).

Organic material	Biogas yield (m^3/kg VS)	Min HRT* (d)
Animal fat	1.00	33
Flotation sludge	0.69	12
Stomach- and gut contents	0.68	62
Blood	0.65	34
Food leftovers	0.47-1.1	33
Rumen contents	0.35	62
Pig manure	0.3-0.5	20
Cattle manure	0.15-0.35	20
Chicken manure	0.35-0.6	30
Primary industrial sewage sludge	0.30	20
Market waste	0.90	30
Waste edible oil	1.104	30
Potato waste (chips residues)	0.692	45
Potato waste (peelings)	0.898	40
Potato starch processing	0.35-0.45	25
Brewery waste	0.3-0.4	14
Vegetable and fruit processing	0.3-0.6	14

*HRT – hydraulic retention time (ie duration of processing before stabilization)

Table 1. Biogas yields from various organic materials conducted in batch tests. Source: Braun (2007).

A wide variety of energy crops can be grown for anaerobic digestion, but maize is by far the most important and it also has a higher potential biogas yield per ha cultivated than most other crops (Hopfner-Sixt & Amon, 2007; Weiland, 2006; Table 2). Since the key factor to be optimised in biogas production is the methane yield per ha, specific harvest and processing technologies and new genotypes will increasingly be used when crops are required as a renewable energy source.

In order to maintain a year-round supply of substrate to the digester, the harvested energy crop must be preserved by ensiling. Optimal ensiling results in rapid lactic acid (5–10 %) and acetic acid fermentation (2–4%), causing a decrease of the pH to 4–4.5 within several days (Braun et al., 2008). Silage clamps or bags are typically used. Improper preparation and storage of silage is critical to successful utilisation in AD plants. For example, Baserga & Egger (1997; cited in Prochnow et al., 2009) demonstrated a remarkable reduction in biogas yields due to aerobic deterioration of grass silage. Immediately after opening of a silage bale the biogas yield was 500 L/kg DM, after five days 370 L and after 30 days only 250 L. Similarly, biogas yields from grass silage cut in summer in southeast Germany produced 216 L/kg DM for a well preserved silage but 155 L for spoiled silage (Riehl et al., 2007; cited in Prochnow et al., 2009).

Special care must also be taken in case of substrate changes. Changing composition, fluid dynamics and bio-degradability of the substrate components can severely impede digestion efficiency resulting in digester failures (Braun et al., 2008). Large scale commercial energy crop digestion plants mainly use solid substrate feeding hoppers or containers for dosing the digester continuously via auger tubes or piston pumps. Commonly energy crops are fed together with manure or other liquid substrates, in order to keep fermentation conditions homogenous.

Crop	Biogas yield (m^3/t VS)	Crop	Biogas yield (m^3/t VS)
Maize (whole crop)	205 – 450	Barley	353 – 658
Wheat (grain)	384 – 426	Triticale	337 – 555
Oats (grain)	250 – 295	Sorghum	295 – 372
Rye (grain)	283 – 492		
Grass	298 – 467	Alfalfa	340 – 500
Clover grass	290 – 390	Sudan grass	213 – 303
Red clover	300 – 350	Reed Canary Grass	340 – 430
Clover	345 – 350	Ryegrass	390 – 410
Hemp	355 – 409	Nettle	120 – 420
Flax	212	Miscanthus	179 – 218
Sunflower	154 – 400	Rhubarb	320 – 490
Oilseed rape	240 – 340	Turnip	314
Jerusalem artichoke	300 – 370	Kale	240 – 334
Peas	390		
Potatoes	276 – 400	Chaff	270 – 316
Sugar beet	236 – 381	Straw	242 – 324
Fodder beet	420 – 500	Leaves	417 – 453

Table 2. Typical methane yields from digestion of various plants and plant materials as reported in literature (Data compilation after Braun, 2007)

The total solids content of feedstock in these systems is usually <10% and mechanical stirrers are used for mixing. The typical two-digester, stirred tank design described above is used in most of these digestion plants. Anaerobic digestion of energy crops requires hydraulic retention times from several weeks to months. Complete biomass degradation (80-90% of VS) with high gas yields is essential to maintain the economic viability and environmental performance of the digestion process.

7. Improving energy efficiency

Combustion in burners for heating purposes is the simplest application for the energy content of biogas, and this can be achieved with comparably high efficiency. Alternatively, biogas is converted into electrical energy by the use of an engine and generator. Combined heat and power (CHP) plants are widely used in AD plants though waste heat is generally under-utilised. It is widely agreed that increased use of waste heat in CHP plants is critical for the long-term economic and environmental performance of AD plants. This is especially the case where the costs of energy crops as feedstock have risen concomitantly with the rapid diffusion of AD plants, for example in Germany (Weiland, 2009).

The use of biogas in CHP simultaneously transfers the chemical energy of methane into electrical power (about 1/3rd) and heat (about 2/3^{rds}). CHPs often result in low overall energy efficiencies because the degree of heat use in many cases is quite small. Of a survey of 41 Austrian digestion plants, CHP energy efficiency ranged from 30.5 to 70.7% (Braun et al., 2008).

Nevertheless, there are examples of the effective use of waste heat in Scandinavian countries where district heating grids are more commonplace (Holm-Nielsen et al., 2009). And in Germany, municipal authorities have developed district heating CHP systems to provide heat and power to businesses and residents in many cities for >100 years (Kerr, 2009).

There is a wide range of CHP technologies commercially available, such as diesel engines converted to run on dual-fuel, gas turbines and Stirling engines (Lantz et al., 2007). These applications are available in size from approximately 10kW$_{el}$ to several MW$_{el}$. Small-scale CHP may prove to be suitable at small, farm-based AD plants although scale effects and the problems concerning the utilisation of the heat discussed above make large-scale applications more economical under current conditions (Lantz et al., 2007).

8. Upgrading of biogas for use in vehicle fuels or natural gas grids

In the EU countries where AD is well-established, upgrading of biogas is increasingly being considered so that it can be injected into the natural gas grid or used as a vehicle fuel. Before biogas is suitable for these applications, it must be upgraded to natural gas quality by the removal of its CO_2 content and other contaminants (e.g. H_2S, NH_3, siloxanes and particulates). Commercially available technologies available to remove CO_2 include pressurized water absorption and pressure swing adsorption.

In response to CO_2 emission reduction targets, the EU biofuels directive set a target of replacing 5.75% of transport fuels with biofuels by 2010. Up to date we have seen a rapid increase in bioethanol and biodiesel production since commercial conversion technologies, infrastructure for distribution, and vehicle technologies, currently favour these types of biofuels (Börjesson & Mattesson, 2007). Their competitiveness has also increased with an increase in the price of crude oil. The production costs of using upgraded biogas as a vehicle fuel in the EU are in the same ball-park as wheat-based ethanol and biodiesel from vegetable oils (Börjesson & Mattesson, 2007). But owing to the increased costs associated with adapting vehicles to run on biogas (+10% to new car prices), its price needs to be 20–30% lower than the price of other vehicle fuels.

However, the use of biogas in this manner has several advantages over bioethanol and biodiesel:

- The net annual energy yield per hectare from the AD of energy crops is potentially about twice that of bioethanol from wheat and biodiesel from rapeseed.
- AD could be integrated with bioethanol and biodiesel production to improve their overall resource efficiency by using their by-products to produce biogas.
- Net greenhouse gas (GHG) savings from the use of biogas as fuel could approach 140-180% due to the dual benefit of avoided emissions from manure storage and the replacement of fossil fuels. In comparison, the likely savings in GHG emissions from biodiesel and bioethanol production and use are much lower.[2]

A prominent example of upgrading biogas and using it for vehicle fuel is Sweden, where the market for such biogas utilisation has been growing rapidly in the last decade. Today there are 15,000 vehicles driving on upgraded biogas in Sweden, and the forecast is for 70,000 vehicles, running on biogas supplied from 500 filling stations by 2012 (Persson et al., 2006). In Sweden, the production of vehicle fuel from biogas has increased from 3TJ in 1996 to almost 500 TJ in 2004 or 10% of the current total biogas production. Yet this corresponds to only 0.2% of Sweden's total use of petrol and diesel.

Germany and Austria have also recently set goals of converting 20% biogas into compressed natural gas by 2020 for more efficient use in CHP systems, gas network injection or vehicle fuel use (Persson, 2007). Weiland (2009) predicts that about 1,000 biogas upgrading plants will be needed to meet the government's objective with a projected investment of €10 billion required. To achieve these targets, the German government has developed a comprehensive program of financial incentives. Germany also currently has the largest biogas upgrading plant in the world located at Güstrow with a capacity of 46 million m^3.

9. Conclusion

The threats of climate change, population growth and resource constraints are forcing governments to develop increasingly stronger policy measures to stimulate the development of renewable energy technologies. Bioenergy offers particular promise since it has the potential to deliver multiple benefits such as: improved energy security, reduced CO_2 emissions, increased economic growth and rural development opportunities. Anaerobic digestion is one of the most promising renewable energy technologies since it can be applied in multiple settings such as wastewater and municipal waste treatment as well as in agriculture and other industrial facilities.

Increasing the efficiency of converting biomass to utilisable energy (ie heat and electricity) is critical for the long-term environmental and financial sustainability of AD plants. Even with

[2] Under Scandinavian conditions where the heat and electricity used in bioethanol and biodiesel plants are generated from renewable sources, the GHG savings could range from 60 to 90%. Where these plants use fossil fuels for heating and electricity, the GHG benefits will be much lower.

generous incentives such as those provided by many EU governments, increasing construction costs and the rising cost of energy crops can put the financial viability of AD plants at risk. Unless improvements in efficiency are found and implemented, these pressures could lead to unsustainable rises in the cost of the incentive schemes that underpin the development of renewable energy technologies.

9.1 Future work

Landscapes that are dominated by arable agriculture have always been subject to change, but increasing concerns over energy security and climate change could precipitate major land-use changes on large areas of land over relatively short time-scales. The impact of a rapidly expanding bioenergy industry in many countries is already under scrutiny due to the emergence of a number of unintended consequences. The unintended consequences include competition for food and land, indirect land use change, and landscape scale impacts on water, biodiversity and social values. Consequently, sustainability assessment systems are now beginning to be developed, and institutional systems are being used to set sustainability targets rather than just to stimulate industry expansion (O'Connell et al., 2009).

Systems need to be developed to monitor and deal with sustainability issues at the local level. In particular, there is a need to explore the sustainability of different pathways for industry development and growth. An important part of this process is to develop the tools to assess the inevitable trade-offs that will result between the different components of sustainability.

In addition to the broader consideration of sustainability, R&D needs that are specific to on-farm AD systems include:

- Developing cost-effective AD systems that are purpose designed for different applications (both large-scale and small scale). The capital cost of many on-farm AD systems has been increasing in recent years and could be over-engineered for many applications.
- Developing new higher-yielding energy crops that use less water, pesticides and fertiliser inputs. These crops should not directly compete with food crops and could be grown on under-utilised farming land.
- Conducting studies to increase the conversion efficiency of energy crops to biogas.
- Improving CHP technologies and distribution systems for utilising waste heat for different heating and cooling applications.

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